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Electrical Engineering Research Laboratory
The University of Texas
Austin, Texas

Report No. 4-07

31 December 1962

OPERATION AND PERFORMANCE OF THE CEDAR HILL METEOROLOGICAL TOWER FACILITY

by

W. S. Mitcham
J. R. Gerhardt

Final Report

Contract AF 19(604)-5556
Project No. 7655
Task No. 76551

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEACH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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ABSTRACT

This report presents a brief survey of the sensor and readout instrumentation associated with the Cedar Hill meteorological tower facility together with an analysis of its performance during the first two years of operations. Factors giving rise to system errors such as those involved in analog-to-digital conversion, digital code conversion, integrator drift, input scaling and sensor malfunctioning are discussed and tabulations are presented of their frequency distributions. Procedures are given for the detection of these errors and for the modifications which have been and will be made for their correction or reduction.

INTRODUCTION

Contract AF 19(604)-5556 between the Air Force Cambridge Research Laboratories and The University of Texas became effective 1 February 1960. This contract covered a period of 34 months for the operation and maintenance of the 1434-foot meteorological tower facility located at Cedar Hill, Texas. This is the Final Report to be prepared under the subject contract. The results of research operations utilizing the tower data will be covered in the Final Report to Contract AF 19(604)-7279.

The following sections, including a brief overall description of the tower system, will give a broad survey of its performance, accuracy, limitations, and pertinent modifications. Reference will be made, where necessary, to the results presented in prior publications.

I. BRIEF DESCRIPTION OF SYSTEM

As a service to the reader in providing background information relevant to the more detailed discussion which will follow involving system performance, a brief discussion will be presented here of the major features of the tower installation. Reference whould be made to the previous publications[1, 2, 3, 4] for more comprehensive studies of the various system components, the performance checks and the data editing procedures.

The tower utilized for this study is located at Cedar Hill, Texas approximately 15 miles southwest of Dallas and serves as the support of

The data readout system is designed primarily to permit digital recording of time averaged meteorological data using five channel teletype code in a programmed sequence on paper tape. This paper tape is designed for compatibility with an IBM 047 tape-to-card punch and as a result is subsequently and automatically converted into three 80-column IBM cards. After scaling and amplification by circuits designed to obtain a standard 2.00 millivolts per mph or degree Fahrenheit, the simultaneous inputs from all 36 data channels are applied to corresponding analog integrating amplifiers which develop a set of voltages proportional to the average of input data over the preselected time. Integration time and data readout cycles can be selected as desired over a fairly wide range. At the close of the accurately timed averaging period the programmer disconnects all data inputs and causes the scanner to apply the integrated voltages in sequence to the digital voltmeter. This coded digital voltmeter output information is then sequentially punched on paper tape. Time, date and certain fixed format information are also punched on the paper tape. After each cycle the scanning equipment is reset and the programmer resets the integrators to zero by shorting out the average voltages previously developed. The five-channel teletype code paper tape is the primary data acquisition system output with a Friden FPC-5 Flexowriter utilized to type an original listing and five copies of the system data. Certain additional features have been incorporated into the system to permit greater versatility in operation. These include multiple sensor cable installations on the tower which can handle the output of additional instruments when desired, a provision to permit strip chart recording without integration of any or all variables and a number of special self-checking, self-starting and reset features. The scanning procedures also include special symbols on the tape for control of the Flexowriter and for use in the tape-to-card conversion process.

II. SYSTEM MALFUNCTIONS AND PERFORMANCE EVALUATION

A. Error Sources Contributing to System Errors

During the two years of operation of the Cedar Hill meteorological tower, the major sources of system errors have been isolated. During this time, tests and calibration procedures have been developed in order to detect and correct the system malfunction errors which occur. The techniques which are briefly discussed are presented in their current stage of development. A complete and detailed discussion of the test and analysis techniques appears in Appendix A of the system Operation and Maintenance Manual.[5]

1. EDVM noise errors

The combined analog-to-digital conversion noise errors and the digital code conversion errors are considered as a single error source for the system. For convenience and brevity, these are referred to as "EDVM (electronic digital voltmeter) noise" errors. Currently, a weekly test called "digit check" is performed on the system to investigate this error source.

The EDVM noise was recognized as a major problem in the spring of 1961 until August 1961, during which time a series of minor improvements were incorporated. In August, a cumulative improvement of an order of magnitude in the error figure was obtained. The improvements were obtained by such techniques as (1) removing system ground loops, (2) installing additional electromagnetic shielding at critical points in the system and (3) isolating and individually arc suppressing by RC networks, suppressor diodes, etc., the major individual electromechanical noise contributors including such components as the Flexowriter (a tape-reading electric typewriter), the tape take-up motors, the tape punch, the stepping switches and the calibration solenoid for the ambient temperature recorder.

Prior to August 1961, the weekly "digit check" showed that errors of plus or minus 0.1 to 0.5 units occurred in 20 to 40 per cent of the data. Errors of a different type called "decade errors" with magnitudes of plus 1.0, 10.0 or 100.0 occurred in 0.01 to 0.1 per cent of the data. After August 1961, errors of plus or minus 0.1 units occurred in 2 to 5 per cent of the data and errors of 0.2 to 0.5 units occurred in 0.01 to 0.1 per cent of the data. Decade errors of plus 1.0, 10.0, 100.0 still occurred in 0.01 to 0.1 per cent of the data. Only small improvements in these figures are anticipated from the system repairs and improvements in early 1963.

2. Integrator drift noise errors

The errors involved in generating the average value of the thirty-six individual data channels over the preselected averaging time intervals are considered for brevity and convenience to be "integrator drift" errors. Since errors from this source were anticipated to be appreciable during the design phase of the system, a twelve-hour automatic calibration was built in. These test data are based on a calibration signal equivalent to a data signal of about 49.5 miles per hour and 49.5 degrees Fahrenheit. Unlike the regular data, these data are read out at an increased sensitivity of (x 14.5) for ten-minute data. The test results contain excess errors due to the test equipment instability, but the tests are made with a dc voltage instead of being slowly time varying as are the data signals. Assuming approximate cancellation by these two effects, the test results are assumed to apply proportionally, since the test results are obtained with a higher resolution than the normal data.

The automatic system calibration at noon and midnight daily has been in operation as long as the system. In February 1962, the averaging circuit gain consistency checks (automatic system calibration) were expanded to include both a positive and negative polarity test signal at noon and midnight daily. With this additional bit of information about the bias nature of certain errors, the detection and repair techniques were improved and some heretofore undetectable small system errors were uncovered and repaired. The other major improvement obtained in this area during the first year of operation was the installation of mechanical spacers in the operational amplifiers which provided more positive plug contacts and eliminated numerous system overloads caused by intermittent poor plug contact.

Over the two-year operation period about 2.7 per cent of the data readings may be expected to have integrator drift errors of plus or minus 0.1 units or larger, referred to normal ten-minute data. With current techniques this figure may be kept in the range of 0.2 to 1 per cent whenever sufficient operator time is available to keep the system in top adjustment and to maintain spare parts for rapid off-line repairs of defective operational amplifiers. During the 1963 shutdown, repairs will be initiated to remove an average system bias which has heretofore amounted to about -0.03 units in the data. Except for the two small improvements above, no major improvements in this portion of the system are anticipated for the 1963 operation.

3. Input scaling noise errors

The errors involved in converting the voltage signals from the various sensors into a uniform signal level suitable for parallel analog averaging are referred to for brevity as "input scaling" noise errors. For the wind signals this involves a passive resistive voltage divider with a gain of 0.03400 when loaded by the integrator averaging circuit. For the ambient temperature circuit this involves a non-linear servo-controlled retransmitting slidewire with an output of 2.00 millivolts per degree Fahrenheit from -25 to

+125 degrees Fahrenheit when loaded by the averaging circuit. The temperature-difference circuits' gain is a nonlinear compensated function of tower temperature requiring an active amplifier. At 10 degrees Fahrenheit, the gain required is 96.86, at 77 degrees Fahrenheit (the equivalent system calibration temperature) the gain required is 88.54 and at 100 degrees Fahrenheit the gain required is 85.76. Gain instabilities (noise) arise from leakage resistance changes (wind circuits, especially) and amplifier gain instabilities (temperature-difference circuits). No ground check is available for the ambient temperature channel.

Very little routine data investigating this error source has been compiled and analyzed during the two years of operation of the system. What information has been obtained indicates that the system error contribution from this source may be one to two times as large as the integrator drift contribution. That is, errors of 0.1 units or larger in the system output may occur due to this source in 2 to 5 per cent of the system readings. The major improvements made in this area during the two years of operation resulted from the recognition of coaxial cable leakage variations as the major source of system noise for the wind channels due to this source and amplifier chopper ripple as the major source of temperature-difference gain instabilities.

A major improvement in the system performance is expected in this area for the operation in 1963. The effects of input scaling noise will be investigated on a routine basis weekly and precise calibrations will be performed monthly. Heretofore, reliance has been placed on the initial system calibration. This more routine and detailed study of this error source will permit more rapid detection and repair of failing circuits and will, in addition, provide a more realistic estimate of the system errors contributed from this source.

4. Instrument errors

Instrument errors are considered to be those errors involved in converting the measured variable into electrical form and in the transmission of this electrical signal to the ground for machine processing. Due to the different techniques employed, the instruments will be discussed separately.

a. Ambient temperature errors

The ambient temperature thermocouple junction and recorder have a rated accuracy of plus or minus 0.7 degrees Fahrenheit. The initial laboratory calibration indicated that the instrument accuracy was within plus or minus 0.6 degrees Fahrenheit over the temperature range 0 to 120 degrees Fahrenheit. The average error over this temperature range was -0.25 degrees Fahrenheit. The single tower recalibration at a single temperature was within 0.3 degrees Fahrenheit of the initial calibration error at the same temperature. No improvements whatever are expected for this instrument during 1963 operation, except for obtaining an additional measure of the instrument calibration stability.

(b) Wind errors

The twenty-four wind data channels measure the average values of the instantaneous north-south and east-west vector components of wind velocity. On a routine basis, the average vector wind velocity for each of twelve measuring elevations is plotted four times each day. The data records obtained are utilized to detect two types of instrument failure:

(1) A sudden drastic and consistent change in the data signal from one or more channels is readily observable. Prompt tests on the ground can determine whether the failure is due to the instrument or to the ground equipment and, if the failure is due to the instrument, it may be readily replaced by an operative spare unit while repairs are performed. Such an instrument replacement may be checked on the tower by a simulated wind velocity test with accuracies of about one mile per hour and 0.2 degrees of azimuth.

(2) If one level of wind data shows consistent departures from the prevailing wind pattern of as much as 3 miles per hour or 4 degrees of azimuth, it is removed for a thorough ground check. Deviations of this small a magnitude are normally acceptable as being due to a small variation in the prevailing wind pattern. However, when the deviation occurs consistently at one level under varying wind conditions, the probability that the deviation, although small, is due to instrument error becomes quite high. In this case, the instrument is replaced after a ground test to insure that the ground readings are consistent with the instrument signal.

Periods where intermittent inconsistencies of about 2 to 15 miles per hour occur in the wind data due to instrument failures have been individually noted in the data editing. The Aerovane tower and ground electrical calibration equipment was not developed until January 1962. In January 1961, the Aerovanes suffered heavy damage due to falling ice. At that time four new Aerovanes were purchased and the eight remaining tower levels were supplied by units rebuilt from the better scraps of the damaged units. Since no spares were available, whatever response the damaged units provided had to be accepted. The unit at level 6 (600 foot elevation) was particularly subject to intermittent failures. By January 1962, spare parts for repairs had been obtained and the electrical calibration equipment was completed which permitted a factory quality overhaul of all tower units damaged by the ice fall of January 1962. All units were reinstalled at this time and as used during 1962 had an initial installation accuracy of plus or minus 2 miles per hour and 2 degrees in azimuth. Except for individual intermittent failures as noted in the data editing, the operational accuracy in 1962 may be estimated to be within 3 miles per hour and 3 degrees in azimuth for the year.

The major improvement in Aerovane performance for 1963 will be a result of more rapid detection of intermittent failures and replacement of the intermittent instrument.

(c) Temperature-difference errors

The eleven temperature-difference channels, like the wind channels, are plotted four times daily as a check on instrument consistency. An additional check utilizes the fact that temperature is a scalar point function rather than a vector field quantity like wind. This check involves the off-line "loop" temperature-difference circuit measuring the temperature-difference between the bottom and the top of the tower. This "loop" measurement is external to the regular system data, but over equivalent time intervals its average value should be the negative of the algebraic sum of the eleven system temperature differences. A monthly "closure error" distribution is prepared from the four daily sample data plots as a measure of the overall system temperature-difference accuracy under actual operating conditions.

If the errors in each temperature-difference circuit are Gaussian, the "closure error" should be Gaussian. A belated analysis of this data has shown that the errors are not Gaussian. The worst months for this error were December 1961, November 1961 and June 1961. The data are summarized with reference to a relatively inaccurate thermistor measurement of the temperature at level 12 (T_{12}) from May 1961 through January 1962. From February 1962 through December 1962, the "loop" thermocouple circuit served as the comparison standard. This circuit has the same inherent accuracy as the system temperature-difference circuits except for the additional error introduced by its strip chart recorder (plus or minus 0.4

degrees Fahrenheit). In addition, it does not penalize the temperature-difference circuits with the plus or minus 0.7-degree Fahrenheit accuracy of the ambient temperature reading. The "closure errors" measured by the "loop" circuit are seen to be more accurate by a factor of 2 to 4 than were obtained using the thermistor comparison circuit. From this, one may conclude that a portion of the "error" should be attributed to the thermistor reference before attributing the remainder to system data errors. On a monthly basis, this comparison may be seen in the appropriate columns of Table I on page 14. The columns on percentage closures for the temperature-differences in Table I are points from an error distribution. That is, the closure error may be expected to exceed the given magnitude of error the tabulated percentage of time.

The closure errors are found to be quite large with respect to the error predicted by the circuit design. An analysis of the effects of leakage from extraneous wind signals shows that the leakage resistance deterioration from its initial value of 1000 megohms to the worst measured value of 20 megohms has reduced the maximum allowable extraneous signal value for negligible error from 6 volts (equivalent to 100 miles per hour in the appropriate wind channel) to 0.1 volts (equivalent to 2 miles per hour in the appropriate wind channel under the worst angle conditions. Under current conditions a wind signal of plus or minus 15 miles per hour could produce an error of as much as plus or minus 0.4 degrees Fahrenheit in the adjacent temperature-difference circuit. Since it is impossible to guarantee that the

TABLE 1

SUMMARY OF SYSTEM MALFUNCTIONS AND PERFORMANCE

	PERFORMANCE			MALFUNCTIONS									
MONTH	TOTAL HOURS OPERATIONAL	HOURS DOWN-TIME	PER CENT DOWN-TIME	① EDVM NOISE % OF READING WITH ERRORS OF .01 OR LARGER IN DATA	② INTEGRATOR DRIFT ERROR % OF READINGS WITH ERRORS OF .01 OR LARGER REFERRED TO 10 MIN. DATA	③ INPUT SCALING ERROR	④ INSTRUMENTS a. AEROVANES MAG	a. AEROVANES ANGLE	b. T_i	c. TEMPERATURE DIFFERENCE AV CLOSURE	% CLOSURE > 1.2°	% CLOSURE > 2.4°	% CLOSURE > 7.2°
DEC. '60	198.7	15.6	7.9		0.2 %		±30	±3°		NO DATA			
JAN. '61	744.0	142.1	19.1							" "			
FEB	672.0	557.8	83.0		DATA TAKEN BUT NOT EVALUATED					" "			
MAR	744.0	118.3	15.9	20%-40% OF READINGS					±0.7°F	" "			
APR	720.0	97.4	13.5		4.5 %					" "			
MAY	744.0	135.1	18.2		3.5 %					-0.01°F	24.6 %	7.0 %	1.8 %
JUNE	720.0	169.7	23.6		2.2 %		±4.0	±4°		-0.32°F	28.1 %	10.4 %	0.0 %
JULY	744.0	205.0	27.6		15.4 %					-0.29°F	23.2 %	1.0 %	0.0 %
AUG	744.0	469.5	63.1		1.9 %					0.00°F	14.3 %	0.0 %	0.0 %
SEPT	720.0	258.5	35.9		3.1 %	INSUFFICIENT DATA TO BE STATISTICALLY SIGNIFICANT.				INSUFFICIENT DATA TO BE SIGNIFICANT			
OCT	744.0	136.0	18.3		0.7 %	DATA TAKEN INDICATES ERRORS ARE EQUIVALENT TO INTEGATOR DRIFT ERRORS WITHIN A FACTOR OF ABOUT 2.				+0.11°F	21.6 %	4.9 %	0.0 %
NOV	720.0	55.2	7.7		0.9 %					-0.68°F	42.9 %	9.2 %	0.0 %
DEC	744.0	183.8	24.7		4.9 %					+0.68°F	68.8 %	47.1 %	10.3 %
JAN. '62	744.0	244.3	32.8		1.7 %					INSUFFICIENT DATA TO BE SIGNIFICANT			
FEB	672.0	192.3	28.6		2.3 %		±2.0	±2°		+0.18°F	12.8 %	2.6 %	0.0 %
MAR	744.0	28.2	3.8	2%-5% OF READINGS	2.8 % *		±3.0	±3°		+0.14°F	5.6 %	1.1 %	0.0 %
APR	720.0	39.5	5.5		1.1 %					+0.07°F	9.0 %	5.1 %	0.0 %
MAY	744.0	54.6	7.3		4.3 %					+0.28°F	11.5 %	2.1 %	0.0 %
JUNE	720.0	57.6	8.0		0.9 %					+0.31°F	10.4 %	0.9 %	0.0 %
JULY	744.0	139.3	18.7		0.2 %					+0.20°F	6.2 %	1.0 %	1.0 %
AUG	744.0	55.3	7.4		0.8 %					-0.26°F	10.2 %	0.0 %	0.0 %
SEPT	720.0	71.5	9.9		0.3 %					INSUFFICIENT DATA TO BE SIGNIFICANT			
OCT	744.0	83.8	11.3							" " " " "			
NOV.	720.0	113.0	15.7							" " " " "			
DEC.	744.0	202.3	27.2							" " " " "			
TOTALS or AVERAGES	17,918.7	3,825.7	21.4%		2.7 %								

* SUBSEQUENT TESTS MORE RIGOROUS

tower potential is within 0.1 volts of ground, errors may be expected from both tower potentials (bias) and wind velocity cross-talk.

A major improvement in this area is to be installed in early 1963. An improved dc shielding technique ("guarding") is to be employed on the temperature-difference sensors which will produce negligible temperature-difference error assuming the worst case leakage of 20 megohms for dc tower potentials up to 500 volts and wind velocities at any azimuth with speeds up to 100 miles per hour. The only unprovable assumption in these figures involves the sensor cable leakage (as opposed to plug leakage) having remained within an order of magnitude of the initially measured values. Once these improvements are incorporated, it is expected that the standard deviation of the Gaussian closure error will be about 0.7 degrees Fahrenheit which corresponds to a standard deviation per temperature-difference channel of about 0.2 degrees Fahrenheit, or about 0.1 degree Fahrenheit if the chart accuracy of the "loop" circuit is eliminated from consideration.

B. Summary of System Malfunctions and Performance

Table 1 summarizes the performance and malfunctions of the system operation during its two years of operation under contract AF 19(604)-5556. The system had an average down time of 28.7 per cent during the first year of operation, 14.6 per cent during the second year of operation and 21.4 per cent over the two year period.

Based on the results of periodic tests, the per cent occurrence of 0.1 units or larger data errors due to EDVM noise was 20 to 40 per cent during part of the first year's operation and this was reduced to 2 to 5 per cent for the remainder of the first year and all of the second year's operation.

The per cent occurrence of 0.1 units or larger data errors due to integrator drift was about 2.7 per cent for the two years' operation. During most of the second year of operation, however, twice as much test data from which the above figures were derived were collected and analyzed.

The per cent occurrence of 0.1 units or larger data errors due to input scaling noise was not thoroughly investigated during the two years of operation. However, based on what data that were taken, it appears that this figure did not exceed 2 to 5 per cent of the readings.

The instrument accuracy of the ambient temperature channel was maintained to about plus or minus 0.7 degrees Fahrenheit during the two years of operation.

The wind channel accuracy was initially plus or minus 3 miles per hour and 3 degrees of azimuth for all winds and azimuth. From January 1961 through January 1962, the wind channel accuracy was not determined. However, an estimate has been made that it was within plus or minus 4 miles per hour and 4 degrees of azimuth except as noted in the data editing. In January 1962, all instruments were overhauled and had an initial installation accuracy of less than plus or minus 2 miles per hour and 2 degrees azimuth at all levels. It is estimated that the accuracy was maintained to within plus or minus 3 miles per hour and 3 degrees of azimuth for the remainder of 1962.

The accuracy with which the temperature at any level is known depends on several factors. For all measurements the accuracy of the ambient temperature channel of about plus or minus 0.7 degrees Fahrenheit enters in. An entire curve of temperature versus elevation plotted from the system data could be shifted toward larger or smaller temperature readings by as much as 0.7 degrees Fahrenheit due to the ambient temperature accuracy. In addition, the shape of the curve depends on the individual accuracies and resolution of the temperature-difference circuits. By utilizing the "loop" temperature-difference circuit, the "closure error" of all eleven temperature-difference circuits may be estimated. The "closure error" of the sum of the eleven data temperature-difference readings plus the "loop" temperature-difference reading measures essentially the difference in temperature between level 12 and level 12 which should be zero at all times. In practice both the resolution and accuracy of the individual data channels cause the "closure error" to be non-zero.

If the errors can be shown to be distributed in a normal or Gaussian manner, and if it may be accurately assumed that the errors of any individual channel are equal, a measure of the standard deviation and probable error of each data channel of temperature difference may be obtained. The second assumption is currently reasonably well justified in practice but unfortunately the first is not. The closure errors can and have been shown to contain non-random errors. The primary sources of these non-random effects will be removed during the system shut-down for maintenance during the spring of 1963. If the techniques employed are successful, it will be possible then to mathematically determine the probable error in each temperature-difference reading. On earlier data, however, this determination becomes too difficult for reasonable analysis. It is, however, quite possible to determine limits or bounds on the system errors - both random and unrandom. Three points on the "closure error" distribution are shown tabulated in the last three columns of Table 1.

C. Changes in Operation for 1963

During the maintenance shutdown in early 1963 major improvements are to be incorporated in the temperature-difference circuits and the input scaling and compensation and scaling circuits. Complete sensor recalibrations will be performed. Some improvements which should result in minor improvements in the EDVM noise and integrator drift error figures will be installed. A general mechanical overhaul of weathered and damaged system components will be performed.

For the 1963 operations, routine data will be reduced to a five- or ten-minute average sampled once every thirty minutes. However, during periods of particular interest (which are the conditions where previously the temperature-difference errors were most likely to be excessively large), data will be sampled as a forty-second average once each minute.

III. PLANNED OPERATIONS DURING THE NEXT YEAR

As described more fully in the previous paragraphs, a period of three to four months will be employed during the first part of 1963 in a complete recalibration and adjustment of the system. To the extent possible, plans are also underway to extend the basic meteorological facility. Thus, it is hoped that, on occasion, it will be possible to obtain pilot balloon observations to elevations significantly above the top of the tower in order to study the low level jet stream at these higher altitudes. Provisions are also being planned to obtain certain moisture measurements possibly using standard microhygrograph recorders. Finally, simple light-weight cup-type anemometers will be used in order to determine the extent of wind interference effects at various levels and at various azimuths.

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